MZ-TH/99-19, WIS-99/21/May-DPP, hep-ph/9905397

Constraining New Physics with the CDF Measurement of CP Violation in $B \to \psi K_S$

Gabriela Barenboim

Institut für Physik - Theoretische Elementarteilchenphysik

Johannes Gutenberg-Universität, D-55099 Mainz, Germany

gabriela@thep.physik.uni-mainz.de

Galit Eyal and Yosef Nir

Department of Particle Physics

Weizmann Institute of Science, Rehovot 76100, Israel

galit@wicc.weizmann.ac.il, ftnir@wicc.weizmann.ac.il

Recently, the CDF collaboration has reported a measurement of the CP asymmetry in the $B \to \psi K_S$ decay: $a_{\psi K_S} = 0.79^{+0.41}_{-0.44}$. We analyze the constraints that follow from this measurement on the size and the phase of contributions from new physics to $B-\overline{B}$ mixing. Defining the relative phase between the full M_{12} amplitude and the Standard Model contribution to be $2\theta_d$, we find a new bound: $\sin 2\theta_d \gtrsim -0.6$ (-0.87) at one sigma (95% CL). Further implications for the CP asymmetry in semileptonic B decays are discussed.

Recently, the CDF collaboration has reported a measurement of the CP asymmetry in the $B \to \psi K_S$ decay [1]:

$$a_{\psi K_S} = 0.79^{+0.41}_{-0.44}, \tag{1}$$

where

$$\frac{\Gamma(\overline{B}^0_{\rm phys}(t) \to \psi K_S) - \Gamma(B^0_{\rm phys}(t) \to \psi K_S)}{\Gamma(\overline{B}^0_{\rm phys}(t) \to \psi K_S) + \Gamma(B^0_{\rm phys}(t) \to \psi K_S)} = a_{\psi K_S} \sin(\Delta m_B t). \tag{2}$$

(Previous searches have been reported by OPAL [2] and by CDF [3].) Within the Standard Model, the value of $a_{\psi K_S}$ can be cleanly interpreted in terms of the angle β of the unitarity triangle, $a_{\psi K_S} = \sin 2\beta$. The resulting constraint is still weak, however, compared to the indirect bounds from measurements of $|V_{ub}/V_{cb}|$, Δm_B and ε_K [4]:

$$\sin 2\beta \in [+0.4, +0.8]. \tag{3}$$

Yet, the CDF measurement is quite powerful in constraining contributions from new physics to the $B - \bar{B}$ mixing amplitude. It is the purpose of this work to investigate this constraint.

We focus our analysis on a large class of models of new physics with the following features:

(i) The 3×3 CKM matrix is unitary. In particular, the following unitarity relation is satisfied:

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0. \tag{4}$$

(ii) Tree-level decays are dominated by the Standard Model contributions. In particular, the phase of the $\bar{B} \to \psi K_S$ decay amplitude is given by the Standard Model CKM phase, $\arg(V_{cb}V^*_{cs})$, and the following bound, which is based on measurements of Standard Model tree level processes only, is satisfied:

$$R_u \equiv \left| \frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}} \right| \lesssim 0.45. \tag{5}$$

The first assumption is satisfied by all models with only three quark generations (that is, neither fourth generation quarks nor quarks in vector-like representations of the Standard Model). The second assumption is satisfied in many extensions of the Standard Model,

such as most models of supersymmetry with R-parity and left-right symmetric (LRS) models. There exist, however, viable models where this assumption may fail, such as supersymmetry without R-parity (see, for example, the discussion in [5,6] or specific multi-scalar models [7]). Within the class of models that satisfies (i) and (ii), our analysis is model-independent.

The effect of new physics that we are interested in is the contribution to the $B-\overline{B}$ mixing amplitude, $M_{12}-\frac{i}{2}\Gamma_{12}$. Our second assumption implies that

$$\Gamma_{12}\approx\Gamma_{12}^{\rm SM}. \tag{6}$$

The modification of M_{12} can be parameterized as follows (see, for example, [8,4]):

$$M_{12}=r_d^2 e^{2i\theta_d}M_{12}^{\rm SM}. \tag{7}$$

The experimental measurement of Δm_B provides bounds on r_d^2 while the new CDF measurement of $a_{\psi K_S}$ gives the first constraint on $2\theta_d$.

The implications for CP violation in B decays of models with the above features has been discussed in refs. [9-17]. Analyses that are similar to ours have also appeared, prior to the CDF measurement, in refs. [18-23,8].

To derive bounds on r_d^2 and $2\theta_d$ we need to know the allowed range for the relevant CKM parameters. Assuming CKM unitarity (4) and Standard Model dominance in tree decays (5), we get:

$$0.005\lesssim|V_{td}V_{tb}^*|\lesssim 0.013, \tag{8}$$

$$0\lesssim\beta\lesssim\pi/6 \ \text{ or } \ 5\pi/6\lesssim\beta\lesssim 2\pi. \tag{9}$$

Note that these ranges are much larger than the Standard Model ranges. The reason for that is that we do not use here the Δm_B and ε_K constraints. These are loop processes and, in our framework, could receive large contributions from new physics.

Let us first update the constraint on r_d^2. To do so, we write the Standard Model contribution to Δm_B in the following way (see [24,4] for definitions and numerical values of the relevant parameters):

$$\left[\frac{2M_{12}^{\rm SM}}{0.471\ ps^{-1}}\right]=\left[\frac{\eta_B}{0.55}\right]\left[\frac{S_0(x_t)}{2.36}\right]\left[\frac{f_{B_d}\sqrt{B_{B_d}}}{0.2\ GeV}\right]^2\left[\frac{V_{td}V_{tb}^*}{8.6\times10^{-3}}\right]^2. \tag{10}$$

The main uncertainties in this calculation come from eq. (8) and from

$$f_{B_d}\sqrt{B_{B_d}} \;=\; 160-240\ MeV. \tag{11}$$

Using

$$\Delta m_B = r_d^2 |2M_{12}^{\rm SM}|, \tag{12}$$

we find:

$$0.3 \lesssim r_d^2 \lesssim 5. \tag{13}$$

Next we derive the new constraint on $2\theta_d$. With the parameterization (7), we have

$$a_{\psi K_S} = \sin 2(\beta+\theta_d). \tag{14}$$

Defining

$$\begin{aligned} \beta_{\rm max} &\equiv \arcsin[(R_u)_{\rm max}], \\ 2\bar\beta_{\rm min} &\equiv \arcsin[(a_{\psi K_S})_{\rm min}], \end{aligned} \tag{15}$$

where both $\beta_{\rm max}$ and $\bar\beta_{\rm min}$ are defined to lie in the first quadrant, we find that the following range for $2\theta_d$ is allowed:

$$2(\bar\beta_{\rm min}-\beta_{\rm max}) \le 2\theta_d \le \pi + 2(\beta_{\rm max}-\bar\beta_{\rm min}). \tag{16}$$

The constraint (16) can be written simply as

$$\sin 2\theta_d \ge -\sin 2(\beta_{\rm max}-\bar\beta_{\rm min}). \tag{17}$$

Within our framework, the allowed range for β is given in (9), that is $2\beta_{\rm max}\approx\pi/3$. Taking the CDF measurement (1) to imply, at the one sigma level,

$$a_{\psi K_S} \gtrsim 0.35, \tag{18}$$

or, equivalently,

$$2\bar\beta_{\rm min} \approx \pi/9, \tag{19}$$

we find $2(\beta_{\rm max}-\bar\beta_{\rm min})\approx 2\pi/9$ and, consequently,

$$\sin 2\theta_d \gtrsim \;-0.6. \tag{20}$$

If we take a more conservative approach and consider the 95% CL lower bound,

$$a_{\psi K_S} \geq 0, \tag{21}$$

or, equivalently,

$$2\bar{\beta}_{\min} \approx 0, \tag{22}$$

we find $2(\beta_{\max} - \bar{\beta}_{\min}) \approx \pi/3$ and, consequently,

$$\sin 2\theta_d \gtrsim -0.87. \tag{23}$$

Eq. (20) (or the milder constraint (23)), being the first constraint on θ_d, is our main result.

There are two main ingredients in the derivation of the bounds (20) and (23). The validity of one of them, that is the bound on $\sin 2(\beta + \theta_d)$ from the value of $a_{\psi K_S}$, depends on the size of contributions to the $b \to c\bar{c}s$ decay that carry a phase that is different from $\arg(V_{cb}V_{cs}^*)$. To understand the effects of such new contributions, we define

$$\theta_A = \arg(\bar{A}_{\psi K_S}/\bar{A}_{\psi K_S}^{\rm SM}), \tag{24}$$

where $\bar{A}_{\psi K_S}$ is the $\bar{B} \to \psi K_S$ decay amplitude. For $\theta_A \neq 0$, eq. (14) is modified into

$$a_{\psi K_S} = \sin 2(\beta + \theta_d + \theta_A). \tag{25}$$

The bounds (20) and (23) apply now to the combination of new phases $\theta_d + \theta_A$. Since, however, $|\sin\theta_A| \leq |\bar{A}_{\psi K_S}^{\rm NP}/\bar{A}_{\psi K_S}^{\rm SM}|$, we expect θ_A to be small. Then, we can still use (20) and (23), with the right hand side relaxed by $\mathcal{O}(\theta_A)$, as lower bounds on $\sin 2\theta_d$. Examining the actual numerical values of the bounds (20) and (23), we learn that for $|\bar{A}_{\psi K_S}^{\rm NP}/\bar{A}_{\psi K_S}^{\rm SM}| \lesssim 0.01$, the effect is clearly unimportant. It takes a very large new contribution, $|\bar{A}_{\psi K_S}^{\rm NP}/\bar{A}_{\psi K_S}^{\rm SM}| \gtrsim 0.4(0.25)$, to completely wash away our one sigma (95% CL) bounds. We are not familiar with any reasonable extension of the Standard Model where the new contribution is that large. For example, in the framework of supersymmetry with R_p, a model independent analysis of supersymmetric contributions to the $b \to c\bar{c}s$ decay [25] finds an upper bound, $|\bar{A}_{\psi K_S}^{\rm SUSY}/\bar{A}_{\psi K_S}^{\rm SM}| \lesssim 0.1$. The bound can be saturated only with light supersymmetric spectrum and maximal flavor changing gluino couplings. In

most supersymmetric flavor models, however, the relevant coupling is of order $|V_{cb}|$ and $|\bar{A}^{\rm SUSY}_{\psi K_S}/\bar{A}^{\rm SM}_{\psi K_S}|$ is well below the percent level. This is the case, for example, in models of universal squark masses, of alignment and of non-Abelian horizontal symmetries (see *e.g.* ref. [6]). In LRS models, with $m(W_R) \gtrsim 1\ TeV$ and $|V^R_{cb}| \sim |V^L_{cb}|$, we have $|\bar{A}^{\rm LRS}_{\psi K_S}/\bar{A}^{\rm SM}_{\psi K_S}| \lesssim 0.01$.

The other ingredient of our analysis, that is the bound on $\sin\beta$ from R_u, suffers from hadronic uncertanties in the determination of the allowed range for R_u. We have used $|V_{ub}/V_{cb}| \lesssim 0.10$. We emphasize, however, that uncontrolled theoretical errors, that is the hadronic modelling of charmless B decays, are the main source of uncertainty in determining the range for $|V_{ub}/V_{cb}|$. It would be misleading then to assign a confidence level to our bound on $\sin 2\theta_d$. (See a detailed discussion in ref. [4].) All we can say is that if indeed $|V_{ub}/V_{cb}| \leq 0.10$ holds, as suggested by various hadronic models, then $\sin 2\theta_d \geq -0.6(-0.87)$ at one sigma (95% CL). The measurement of $a_{\psi K_S}$ would not provide any bound on $\sin 2\theta_d$ at one sigma (95% CL) if $|V_{ub}/V_{cb}|$ were as large as 0.17 (0.15).

When investigating specific models of new physics, it is often convenient to use a different parameterization of the new contributions to M_{12}. Instead of (7), one uses (see, for example, [22] in the supersymmetric framework and [26] in the left-right symmetric framework):

$$M_{12}^{\rm NP} = he^{i\sigma} M_{12}^{\rm SM}, \tag{26}$$

where $M_{12}^{\rm NP}$ is the new physics contribution. The relation between the two parametrizations is given by

$$r_d^2 e^{2i\theta_d} = 1 + he^{i\sigma}. \tag{27}$$

To derive the CDF constraints in the (h,σ) plane, the following relations are useful:

$$r_d^2 = \sqrt{1 + 2h\cos\sigma + h^2}. \tag{28}$$

$$\sin 2\theta_d = \frac{h\sin\sigma}{\sqrt{1 + 2h\cos\sigma + h^2}}. \tag{29}$$

The bound of eq. (13) corresponds to the allowed region in the (h,σ) plane presented in Figure 1.

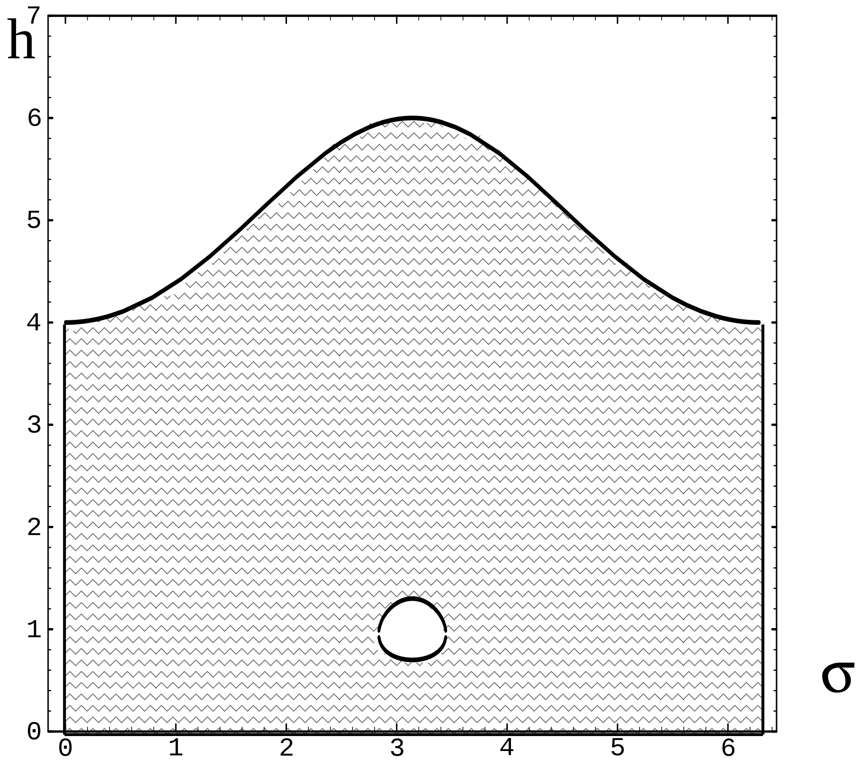

Figure 1. The Δm_B constraint. The grey region is allowed.

The situation is particularly interesting for values of σ close to π. Here, the Standard Model and the new physics contributions add destructively. Consequently, large values of h up to

$$h_{\max} = (r_d^2)_{max} + 1 \approx 6 \tag{30}$$

are allowed; this means that new physics may still be dominant in $B - \overline{B}$ mixing. On the other hand, values of h close to 1 are forbidden since the new physics contribution cancels the Standard Model amplitude, yielding values of Δm_B that are too small.

The bounds of eqs. (20) and (23) are presented in Figure 2.

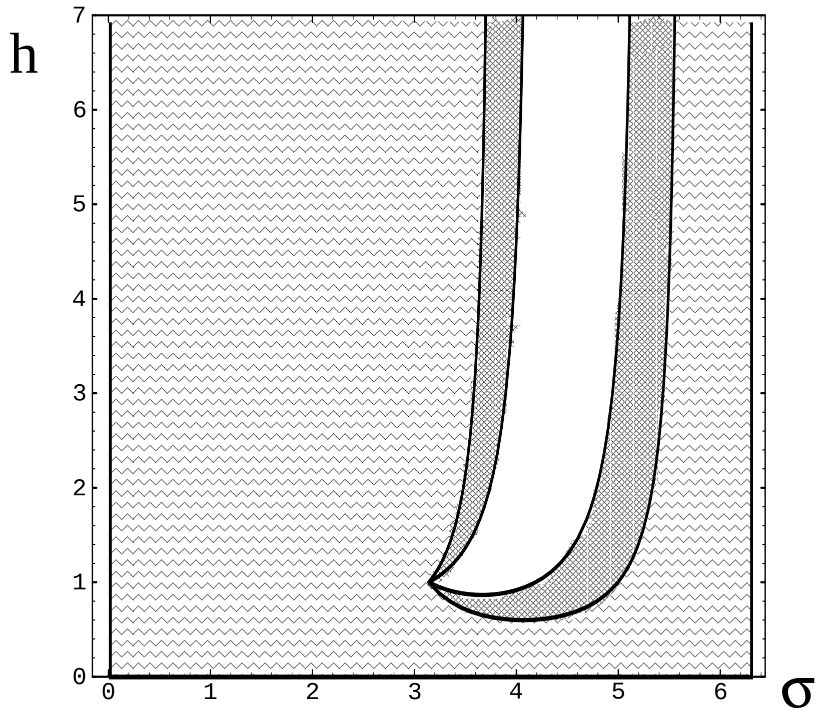

Figure 2. The $a_{\psi K_S}$ constraint. The allowed region corresponding to the one sigma (95% CL) bound, $a_{\psi K_S} \geq 0.35$ (0), is given by the light (light plus dark) grey area.

We would like to emphasize some features of the excluded region:

1. Since only negative $\sin 2\theta_d$ values are excluded, only negative $\sin\sigma$ values are excluded.

2. For very large h, the Standard Model contribution is negligible and, consequently, $\sin\sigma \approx \sin 2\theta_d$. Therefore, for large h values, σ-values in the range $[\pi + 2(\beta_{\max} - \bar{\beta}_{\min}), 2\pi - 2(\beta_{\max} - \bar{\beta}_{\min})]$ are excluded.

3. For σ arbitrarily close to π (from above), there is always an excluded region corresponding to h similarly close to 1.

Finally, in Figure 3 we show the combination of the Δm_B and $a_{\psi K_S}$ bounds. It is obvious that the latter adds a significant exclusion region in the (h, σ) plane.

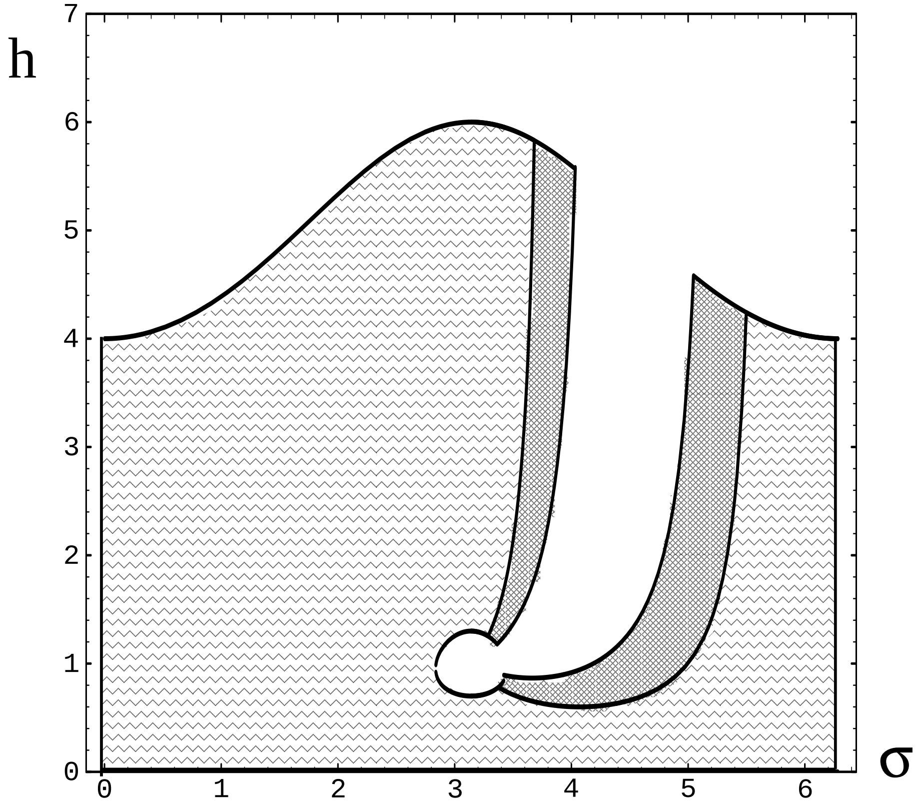

Figure 3. The combination of the Δm_B and $a_{\psi K_S}$ constraints. The light (light plus dark) grey region is the allowed region corresponding to the one sigma (95% CL) bound, $a_{\psi K_S} \geq 0.35$ (0).

The parameters that we have constrained here are related to other physical observables. The ratio between the difference in decay width and the mass difference between the two neutral B mesons, $\Delta\Gamma_B/\Delta m_B$, and the CP asymmetry in semileptonic decays, $a_{\rm SL}$, are given by

$$\begin{aligned} \frac{\Delta\Gamma_B}{\Delta m_B} &= \mathcal{R}e\frac{\Gamma_{12}}{M_{12}}, \\ a_{\rm SL} &= \mathcal{I}m\frac{\Gamma_{12}}{M_{12}}. \end{aligned} \tag{31}$$

The Standard Model value of Γ_{12}/M_{12} has been estimated [27-29,23]:

$$\left(\frac{\Gamma_{12}}{M_{12}}\right)^{\rm SM} \approx -(0.8\pm 0.2)\times 10^{-2}, \tag{32}$$

$$\arg\left(\frac{\Gamma_{12}}{M_{12}}\right)^{\rm SM} = \mathcal{O}\left(\frac{m_c^2}{m_b^2}\right). \tag{33}$$

We emphasize that there is a large hadronic uncertainty in this estimate, related to the assumption of quark-hadron duality. Eq. (32) leads to the following estimates:

$$\begin{aligned} \left|(\Delta\Gamma_B/\Delta m_B)^{\rm SM}\right| &\sim 10^{-2}, \\ |(a_{\rm SL})^{\rm SM}| &\lesssim 10^{-3}. \end{aligned} \tag{34}$$

The (possible) measurement of $a_{\rm SL}$ can be used to constrain the Standard Model CKM parameters [23].

Since $(\Gamma_{12}/M_{12})^{\rm SM}$ is real to a good approximation, the effects of new physics, within our framework, can be written as follows:

$$\begin{aligned} \frac{\Delta\Gamma_B}{\Delta m_B} &= \left(\frac{\Gamma_{12}}{M_{12}}\right)^{\rm SM} \frac{\cos 2\theta_d}{r_d^2}, \\ a_{\rm SL} &= -\left(\frac{\Gamma_{12}}{M_{12}}\right)^{\rm SM} \frac{\sin 2\theta_d}{r_d^2}. \end{aligned} \tag{35}$$

Note the following relation between the two observables:

$$\sqrt{(\Delta\Gamma_B/\Delta m_B)^2 + (a_{\rm SL})^2} = \left|\frac{\Gamma_{12}}{M_{12}}\right|^{\rm SM} \frac{1}{r_d^2}. \tag{36}$$

The lower bound on r_d^2 in eq. (13) implies then that neither $\Delta\Gamma_B/\Delta m_B$ nor $a_{\rm SL}$ can be enhanced compared to $(\Gamma_{12}/M_{12})^{\rm SM}$ by more than a factor of about 3, that is a value of approximately 3×10^{-2}. Moreover, if one of them is very close to this upper bound, the other is suppressed. (This is actually the situation within the Standard Model: $\Delta\Gamma_B/\Delta m_B$ saturates the upper bound with $r_d = 1$, and $a_{\rm SL}$ is highly suppressed.)

The new bound on $\sin 2\theta_d$ that we found, eq. (20) (or the milder bound (23)), do not affect the allowed region for $\Delta\Gamma_B/\Delta m_B$. The reason is that $\cos 2\theta_d$ is not constrained and could take any value in the range $[-1,+1]$. On the other hand, the range for $a_{\rm SL}$ is affected. Taking into account also the lower bound on r_d^2 in (13), we find

$$-3.3 \lesssim \frac{a_{\rm SL}}{(\Gamma_{12}/M_{12})^{\rm SM}} \lesssim 2.0. \tag{37}$$

The reduction in the upper bound from 3.3 to 2.0 is due to the $a_{\psi K_S}$ bound. Note that $(\Gamma_{12}/M_{12})^{\rm SM}$ is negative, so that the $a_{\psi K_S}$ constraint is a restriction on negative $a_{\rm SL}$ values.

Similar analyses will be possible in the future for the B_s system. At present, there is only a lower bound on Δm_{B_s},

$$\Delta m_{B_s} \ \geq \ 12.4 \ \mathrm{ps}^{-1}. \tag{38}$$

The main hadronic uncertainty comes from the matrix element,

$$f_{B_s}\sqrt{B_{B_s}} \ = \ 200 - 280 \ MeV. \tag{39}$$

We find

$$r_s^2 \gtrsim 0.6. \tag{40}$$

Consequently, $|a_{\rm SL}(B_s)|$ is constrained to be smaller than 1.6 times the Standard Model value of $|\Gamma_{12}(B_s)/M_{12}(B_s)|$.

Once an upper bound on a CP asymmetry in B_s decay into a final CP eigenstate is established, we will be able to constrain $2\theta_s$. It will be particularly useful to use $b \to c\bar{c}s$ decays, such as $B_s \to D_s^+ D_s^-$. The Standard Model value, $a_{B_s \to D_s^+ D_s^-} \approx \sin 2\beta_s$, is very small, $\beta_s \equiv \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)] = \mathcal{O}(10^{-2})$. Therefore, the Standard Model contribution can be neglected when the bounds on $a_{B_s \to D_s^+ D_s^-}$ are well above the percent level. The approximate relation, $a_{B_s \to D_s^+ D_s^-} \approx -\sin 2\theta_s$, will make the extraction of a constraint on $\sin 2\theta_s$ particularly clean and powerful.

To summarize our main results: the CDF measurement of the CP asymmetry in $B \to \psi K_S$ constrains the size and the phase of new physics contributions to $B-\bar{B}$ mixing. The constraints are depicted in Figures 2 and 3. They can be written as a lower bound, $\sin 2\theta_d \gtrsim \ - 0.6 \ (-0.87)$ at one sigma (95% CL), where $2\theta_d = \arg(M_{12}/M_{12}^{\rm SM})$. This, together with constraints from Δm_B, gives the one sigma bounds on the CP asymmetry in semileptonic B decays, $-2 \times 10^{-2} \lesssim a_{\rm SL} \lesssim 3 \times 10^{-2}$.

Acknowledgements

We thank Yuval Grossman and Mihir Worah for valuable comments on the manuscript. G.B. acknowledges a post-doctoral fellowship of the Graduiertenkolleg "Elementarteilchenphysik bei mittleren und hohen Energien" of the University of Mainz. Y.N. is supported

in part by the United States – Israel Binational Science Foundation (BSF) and by the Minerva Foundation (Munich).

References

[1] T. Affolder *et al.*, CDF collaboration, hep-ex/9909003.

[2] K. Ackerstaff *et al.*, Eur. Phys. J. C5 (1998) 379, hep-ex/9801022.

[3] F. Abe *et al.*, Phys. Rev. Lett. 81 (1998) 5513, hep-ex/9806025.

[4] The BaBar Physics Book, eds. P.F. Harrison and H.R. Quinn, SLAC-R-504 (1998).

[5] Y. Grossman and M.P. Worah, Phys. Lett. B395 (1997) 241, hep-ph/9612269.

[6] R. Barbieri and A. Strumia, Nucl. Phys. B508 (1997) 3, hep-ph/9704402.

[7] K. Kiers, A. Soni and G.-H. Wu, Phys. Rev. D59 (1999) 096001, hep-ph/9810552.

[8] Y. Grossman, Y. Nir and M.P. Worah, Phys. Lett. B407 (1997) 307, hep-ph/9704287.

[9] Y. Nir and D. Silverman, Nucl. Phys. B345 (1990) 301.

[10] C.O. Dib, D. London and Y. Nir, Int. J. Mod. Phys. A6 (1991) 1253.

[11] J.M. Soares and L. Wolfenstein, Phys. Rev. D47 (1993) 1021.

[12] Y. Nir, Phys. Lett. B327 (1994) 85, hep-ph/9402348.

[13] Y. Grossman, Phys. Lett. B380 (1996) 99, hep-ph/9603244.

[14] N.G. Deshpande, B. Dutta and S. Oh, Phys. Rev. Lett. 77 (1996) 4499, hep-ph/9608231.

[15] J.P. Silva and L. Wolfenstein, Phys. Rev. D55 (1997) 5331, hep-ph/9610208.

[16] A.G. Cohen, D.B. Kaplan, F. Lepeintre and A.E. Nelson, Phys. Rev. Lett. 78 (1997) 2300, hep-ph/9610252.

[17] G. Barenboim, F.J.Botella, G.C.Branco and O.Vives, Phys. Lett. B422 (1998) 277, hep-ph/9709369.

[18] T. Goto, N. Kitazawa, Y. Okada and M. Tanaka, Phys. Rev. D53 (1996) 6662, hep-ph/9506311.

[19] Z. Xing, Eur. Phys. J. C4 (1998) 283, hep-ph/9705358.

[20] A.I. Sanda and Z. Xing, Phys. Rev. D56 (1997) 6866, hep-ph/9708220.

[21] L. Wolfenstein, Phys. Rev. D57 (1998) 6857, hep-ph/9801386.

[22] L. Randall and S. Su, Nucl. Phys. B540 (1999) 37, hep-ph/9807377.

[23] R.N. Cahn and M.P. Worah, hep-ph/9904480.

[24] G. Buchalla, A.J. Buras and M.E. Lautenbacher, Rev. Mod. Phys. 68 (1996) 1125, hep-ph/9512380.

[25] M. Ciuchini, E. Franco, G. Martinelli, A. Masiero and L. Silvestrini, Phys. Rev. Lett. 79 (1997) 978, hep-ph/9704274.

[26] G. Barenboim, Phys. Lett. B443 (1998) 317, hep-ph/9810325.

[27] J.S. Hagelin, Nucl. Phys. B193 (1981) 123.

[28] A.J. Buras, W. Slominski and H. Steger, Nucl. Phys. B245 (1984) 369.

[29] M. Beneke, G. Buchalla and I. Dunietz, Phys. Rev. D54 (1996) 4419, hep-ph/9605259.